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BONDING STRENGTHS OF ADHESIVES AT NORMAL AND LOW TEMPERATURES

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SUMMARY

The bonding strengths of two thermosetting adhesives, liquid Cycleweld C-3 and Ardux 1, to several aircraft materials were determined by shear tests made on lap-joint specimens. A few specimens were made with Cycleweld C-3 film. The specimens were tested at 25° C and at subfreezing temperatures of approximately -40° C.

With phenolic laminates both adhesives produced bonds sufficiently strong so that the test specimens failed in the laminate rather than in the bond. To obtain the maximum shear strength in the Compreg specimens it was necessary to preheat the material first to relieve the high residual stresses and then machine the strips to obtain flat surfaces. The shear strengths of the Cycleweld-bonded metal specimens were greater than those of the Ardux-bonded specimens; also the strength of the former increased while the strength of the latter decreased when the tests were made at low temperatures.

The shear strengths obtained for specimens made from aluminum alloy bonded to magnesium alloy with Cycleweld C-3 cement were comparable to the values obtained for the specimens in which strips of the same metal were attached together. An increase in shear strength with decrease in temperature was again observed.

The shear strength of the birch-faced plywood and aluminum-alloy specimens bonded with Cycleweld C-3 was much greater than that for similar specimens containing mahogany-faced plywood. For both plywoods the shear strengths of the lap-joint specimens made with the resin-coated or the uncoated materials were practically the same,

and the major portion of the failure generally occurred in the wood veneer rather than in the adhesive. Also, the shear strengths of the specimens made with birch plywood were generally greater at subfreezing temperatures than at 25° C while the reverse was true for the mahogany-plywood and aluminum-alloy specimens. Satisfactory results were obtained for some aluminum-alloy and plywood specimens bonded with Cycleweld C-3 film.

INTRODUCTION

In the construction of aircraft the attachment of component structural elements is accomplished by various means, such as riveting, bolting, welding, and in some instances by gluing. While present procedures are generally satisfactory, it is possible that, provided suitable adhesives can be found, gluing might be the most rapid and satisfactory method of assembly. This method is now used widely in plywood construction.

Sometimes it is necessary in assembling an aircraft structure to attach together parts made of different materials, such as plywood to metal, or plastic to metal. This situation complicates the search for a suitable adhesive owing to various factors such as unequal effects of temperature and humidity variations upon the materials to be attached, the relative permeability of the materials to the adhesive, and other factors.

In selecting an adhesive suitable for bonding aircraft structural elements it must be borne in mind that good adhesive strength as determined under laboratory conditions is not the only criterion. The adhesive should retain a high strength at subfreezing as well as tropical temperatures, and under vibratory loads. Retention of strength when exposed to chemical reagents such as water, aviation gasoline, ethylene glycol, and dope solvents is often important. The tendency to creep under possible service conditions should also be negligible. The thermosetting adhesives can be expected to be less affected by solvents and to exhibit less creep at the highest temperatures encountered in service than thermoplastic adhesives.

In this country a thermosetting adhesive, Cycleweld C-3, has been developed for bonding metal sheets together. In

England a synthetic thermosetting resin, Ardux 1, has been developed for bonding phenolic plastics together.* The possibilities of these adhesives for use in bonding aircraft parts were investigated as part of a research project carried on at the National Bureau of Standards, sponsored by and conducted with the financial assistance of the National Advisory Committee for Aeronautics.

MATERIALS AND SPECIMENS

The materials which were bonded together with the adhesives are described in table 1. The lap-joint type of specimen was chosen for testing the bonding properties of the adhesives because of the ease with which such specimens could be formed and tested. The specimen was generally about 6 to 8 inches long and 0.7 inch wide with an overlap of 0.5 inch. For some tests the material or materials to be bonded were cut into strips 3 to 4 inches long and of the desired width (i.e., 0.7 inch) and the strips bonded to form specimens ready for test. In another procedure, sheets of the materials 3 to 8 inches in width were overlapped and bonded, and the test specimens sawed or sheared from the lap-jointed panels. Prior to bonding, the metal strips and sheets were cleaned by either abrading or washing with petroleum naphtha and the surfaces of the plywoods and of some of the plastics were roughened with sandpaper.

The Cycleweld C-3 adhesive was supplied in both liquid and film form. For this adhesive, it was recommended by the manufacturer that the bonding be done under pressure and the temperature at the bond be maintained at 163° C (325° F) for at least 15 minutes. The Ardux 1 was supplied in the form

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*Recently Amberlite PR-65, an adhesive comparable to Ardux 1, has become available in this country. Tests made with lap-joint specimens of paper-base laminate, 1/16 inch thick, and fabric-base laminate, 1/4 inch thick, showed that these two adhesives had identical bonding strength. Unabraded specimens of the paper-base laminate had shearing strengths of 920 and 900 psi when bonded with Ardux 1 and Amberlite PR-65, respectively. Unabraded specimens of the fabric-base laminate had shearing strengths of 2040 and 2050 psi when bonded with Ardux 1 and Amberlite PR-65, respectively. Abrasion of the surfaces of the laminates before bonding with Amberlite PR-65 had no effect on the strength of the bond.

of a thick liquid and the curing conditions suggested for it were clamping pressure and a temperature of at least 140° C. When bonding materials with the liquid adhesives, the two surfaces to be adhered were coated with the adhesive.

Since the Compreg and, to a lesser degree, some phenolic laminates presented difficulty in bonding because they unmolded,* specimens were prepared in which strips of the materials had been given one of the following treatments: (a) surface unabraded, (b) surface abraded, (c) strip preheated for 1 hour at 145° C, and (d) strip preheated for 1 hour at 145° C and the surface abraded. The specimens were made from identical strips of the Compreg and of the 0.25-inch-thick phenolic laminates. To determine the strength of Compreg lap-joint specimens with the material free of residual stresses and the bonding surfaces flat, strips which had been preheated were machined on one face to give a flat surface for bonding. Specimens were made with both adhesives, and both unabraded and abraded materials were used.

These specimens were cured in an oven with a spring-and-clamp device which allowed control of the bonding pressure. The "spring-clamp" apparatus is shown in figure 1 with a pack of specimens in place. In addition to permitting control of the initial clamping pressure, the spring-clamp device allowed the strips to increase in thickness, if they unmolded, without large variation in the pressure.

To insure that the bond was held at the desired curing temperature for a sufficient time, in several specimens the temperature was measured with a thermocouple located in the bond. Each couple was made of No. 40 wire soldered with a lap-joint and laid parallel to the length of the specimen.

To test the suitability of Cycleweld C-3 cement for bonding aluminum alloy to magnesium alloy, 24S-T alclad sheet 0.025 inch thick was bonded to J-1 magnesium alloy sheet 0.032 inch thick with liquid cement. Two sets of specimens were made; one in the spring-clamp apparatus, the other in a steam-heated press. In the first set, the magnesium strips were cleaned with sandpaper, washed with water, and wiped dry, and the aluminum alloy was cleaned with pumice soap and water and wiped dry. The second set of specimens

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*Unmolding refers to the swelling or distortion that plastics may exhibit when residual stresses are released, a process accelerated by elevating the temperature.

was taken from lap-joint panels made from pieces of metal 3 by 4 inches. The aluminum alloy material was cleaned as before; the magnesium alloy pieces were abraded with sandpaper but were not washed.

EQUIPMENT AND TEST PROCEDURE

The width and the length of the bonded area of each specimen were measured with a steel scale graduated in hundredths of an inch. The specimens were tested in shear on the 2400-pound range of a 60,000-pound-capacity Baldwin-Southwark hydraulic testing machine, accurate to ±5 pounds over the range used. The rate of head separation was maintained at 0.05 inch per minute, and the time to break each specimen was recorded. The testing machine was located in a conditioned laboratory in which the temperature was maintained at 25° C and the relative humidity at 50 percent.

For the low-temperature tests, an insulated box was constructed to enclose the grips. The box was cooled with solid carbon dioxide. Two armholes were cut in the front, and leather gloves were attached to the edges of the holes so that specimens could be inserted in the grips of the testing machine without opening the box. A double-glazed window and lights mounted inside the box facilitated handling of the test specimens. When the specimens were placed in the box, a thermocouple was attached to each specimen near the bonded portion. The specimens were kept in the cold box for at least 1 hour prior to testing in order to attain temperature equilibrium.

After the specimens were tested, they were examined to determine (a) the percentage of the overlapped area in which the failure occurred in the adhesive, (b) the percentage of the overlapped area in which the adhesive coatings on the two halves of a specimen failed to bond together, (c) the percentage of the overlapped area in which failure occurred in the material bonded, and (d) the percentage of the overlapped area in which failure occurred at the interface between the adhesive and the plastic or metal.

The shear strength was calculated in two ways. First, the breaking load was divided by the shearing area to obtain the average shear stress at failure. Second, the shear strength per inch of bond width was obtained by dividing the breaking load by the specimen width, nominally 0.7 inch.

RESULTS AND DISCUSSION

Specimens Bonded under Clamping Pressure

The data on shear strength for the lap-joint specimens formed under clamping pressure with Cycleweld C-3 cement and Ardux 1 adhesive are shown in tables 2 and 3, and representative specimens after test are shown in figures 2, 3, and 4.

The fabric-base phenolic laminate specimens bonded with Cycleweld C-3 (table 2) were about three-fourths as strong as those bonded with Ardux 1 (table 3). The difference was less marked for the paper-base material. For both adhesives at both 25° C and -40° C the failure was almost entirely within the material rather than in the adhesive or at the adhesive-plastic boundary. The lower shear strength of the Cycleweld-bonded specimens was probably caused by the higher clamping pressure employed in making these specimens. This caused some bending (see fig. 3, specimen E) at the end of the overlapped area.

The Ardux-bonded specimens made from strips of the 1/4-inch-thick phenolic laminates exhibited shear strengths more than twice those shown in the corresponding 1/16-inch-thick material. This may be explained by the fact that the stress distribution at the ends of the overlapped area was different for the two thicknesses when the length of the overlap was the same.

It might be expected that the shear strength, a fictitious or average value, would be the same for a given material if the ratio of length of overlap to thickness of material was maintained constant. Some data that lend weight to this assumption were obtained by determining the strengths of lap-joint specimens of material FL-1/16-A bonded with Ardux and made with three overlaps, 1/8, 1/2, and 1-1/2 inches. The results of these tests, made at 25° C only, are presented in table 4. In all these tests the failure was 97 to 100 percent within the material rather than in the adhesive. If the average shear strength value for the FL-1/16-A specimens with an overlap of 1/8 inch is compared with that for the FL-1/4 specimens (table 3) which had an overlap of 1/2 inch, it is noted that the values are very nearly equal. The ratios of measured overlap to thickness are 1.9 for the FL-1/16-A and 2.0 for the FL-1/2 materials, respectively.

For the metal specimens bonded with Cycleweld C-3, the average shear strengths varied from 1330 to 2530 psi at 25° C, and from 1500 to 3040 psi at -40° C. The type of failure obtained with the metal specimens bonded with Cycleweld C-3 was different at the two temperatures. This is shown in figure 2, comparing specimen A with B, and specimen C with D. At 25° C the major portion of the failure occurred within the adhesive, while at -40° C the major part of the failure occurred at the adhesive-metal boundary.

The metal specimens bonded with Ardux yielded lower average shear strength values than the Cycleweld specimens. The range for the Ardux-cemented specimens was from 230 to 1170 psi at 25° C and from 625 to 870 psi at -40° C. In general, the Ardux-bonded specimens showed a reduction in strength at the low temperature, which is in the opposite direction to the results obtained with Cycleweld-bonded metal strips. There was no marked difference between the 25° C and the -40° C samples with regard to the location of the failure which, except for specimens made with AD-31 aluminum alloy, was located mostly at the adhesive-metal boundary.

None of the Ardux-bonded specimens failed in the metal. With the Cycleweld C-3, however, a few specimens of the aluminum alloy D-10 failed in the metal. These failures are shown in figure 2, specimens E and F. The mean tensile stresses existing in the strips of the various materials at the maximum load were calculated, and these values are shown in table 5 for comparison with the tensile test results presented in table 6. For the Cycleweld-bonded specimens of both aluminum alloy D-10 and stainless steel, the computed tensile stress was about equal to the tensile strength of the metal.

Tests were made to determine whether the materials had been appreciably weakened by the heating to which they were subjected in bonding. Strips of the various materials, 0.7 by 8 inches in size were cut and the edges sanded. One set of strips was tested in tension on the Baldwin-Southwark hydraulic testing machine. Another set of specimens was heated in the oven at about 150° C for 40 minutes, exposed for at least 24 hours in the conditioning atmosphere and then tested. From the results of these tests, shown in table 6, there was some indication that the heat weakened the plastic materials slightly.

Specimens Bonded after Various Surface Treatments

The results of the tests on specimens made from Compreg and phenolic laminate materials, which had various surface treatments prior to bonding, are shown in tables 7 and 8 for the Cycleweld C-3 and Ardux 1 adhesives, respectively. The appearance of some specimens after test is shown in figures 5 and 6.

The results obtained with Compreg show that the unabraded types had the lowest shear strengths, the abraded variety was intermediate, and the specimens which had been preheated and then machined exhibited the highest shear strengths. The kinds of failure for the various types of specimen were quite different; for the machined specimens bonded with Cycleweld (fig. 5, specimens D and E) a considerable part of the failure occurred in the Compreg; while for the other types (fig. 5, specimens F and G) the major portion was at the Cycleweld - Compreg boundary. The Ardux-bonded machined specimens failed principally in the Compreg with no significant difference between the behavior at normal and at low temperature. Typical failues are shown in figure 5, specimens B and C.

The bond strength of the paper base phenolic laminate PL-1/4, adhered with Cycleweld, was greater at low temperature, the increases ranging from 36 to 80 percent. The percentage of failure within the phenolic laminate was much greater at the low temperature, and the percentage of failure within the adhesive decreased. These results are similar to those observed with the Compreg specimens. Typical failures are shown in figure 6; compare A with B, and C with D. With the Ardux cement the failure was practically 100 percent in the laminate at both temperatures. Even though both cements were sufficiently strong so that the failures were practically entirely in the material, the shear strength values obtained for Cycleweld were greater. It was suspected that the Ardux 1 may have weakened the phenolic plastic near the bond because of the chemical reaction of the cement with the plastic.

Specimens of Metal Bonded to Plywood

The data for the shear strength of lap-joint specimens of aluminum alloy bonded to plywood with Cycleweld C-3 cement are shown in tables 9 and 10, and figures 7 through 9 show representative specimens after test.

With the mahogany-aluminum specimens (table 9) there was little difference between shear strength values obtained at 25° C with or without a resin coating. The strength at 25° C obtained with the paper- and resin-faced plywood MRP was considerably lower than that for uncoated and resin-coated plywood. For all types the failure was practically 100 percent in the wood veneer and not in the adhesive (see fig. 7). In most instances the shear strength at the low temperature was somewhat less than that at 25° C.

The shear strength obtained for the mahogany-aluminum specimens bonded with Cycleweld C-3 cement film was found to be about 15 percent less at 25° C than the values obtained with the liquid Cycleweld bonds, and about equal at -40° C to the values obtained with the liquid Cycleweld bonds. The failures for the film-bonded specimens made with the AD-26 and D-22 aluminum alloy occurred 75 percent in the wood, while for the D-30 film-bonded specimens, cured in the press, 96 percent of the failure occurred in the wood.

The birch-aluminum specimens exhibited considerably greater bond strengths than those made with mahogany (table 10). For the specimens bonded with liquid Cycleweld cement, the untreated and resin-treated plywood had greater strength at -40° C than at 25° C, which is the opposite of the results obtained for the specimens made with mahogany plywood. Except for the D-30/B specimens, the failures at low temperature for the six groups were nearly 100 percent in the wood. A typical failure is shown in figure 8, specimen F. From an examination of the D-30/B specimens, it is believed that the high percentage of failure at the metal-adhesive boundary and the low strength may have been caused by insufficient cleansing of the surface of the metal.

For the film-bonded birch-aluminum specimens, those made with the spring-clamp apparatus exhibited shear strengths much lower than the values obtained for specimens bonded with liquid cement; the specimens made in the press exhibited shear strengths almost equal to the values obtained for the specimens bonded with liquid cement. Some film-bonded specimens are shown in figure 9.

The specimens in which the face grain of the plywood was transverse yielded shear strength values much less than for the types in which the face grain was parallel to the length.

Specimens of Aluminum Bonded to Magnesium

The shear strength data for the lap-joint specimens of aluminum alloy bonded to magnesium alloy with Cycleweld C-3 cement are shown in table 11.

The specimens bonded in a press had shear strengths considerably lower than those made with a spring-clamp apparatus, although the percentage failure to bond in the overlapped section was much higher for the latter type. This result may have been caused by the difference in the method of cleaning the magnesium alloy for the two sets of specimens or deterioration of the cement on storage subsequent to preparing the spring-clamp bonded specimens. The failure to bond over a large portion of the area for the spring-clamp specimens was probably caused by a relatively uneven coating of Cycleweld. In both sets of specimens the strength at −40° C was considerably greater than that at 25° C, which is in agreement with the results obtained with other metal specimens. (See table 2.)

Since there was a possibility that the curing operation might weaken the magnesium alloy material, tensile tests were made upon two sets of machined tensile coupons: one set was given the same heat treatment as the lap-joint specimens; the other was not heated. Stress-strain data were taken in these tests which were made at 25° C. The tensile strength of the magnesium alloy was practically unaffected by the heating cycle used to cure the Cycleweld, the average values being 44,900 and 43,900 psi for unheated and heated specimens, respectively, at 25° C. The yield point, however, was affected slightly: for 0.4 percent offset the stress was reduced from 39,500 psi to 35,800 psi by the heat treatment. The few tests made upon the magnesium alloy indicate the necessity for checking the effect of the heating cycle upon the strength of magnesium alloy parts which are to be bonded with Cycleweld.

CONCLUDING REMARKS

Both Ardux 1 and liquid Cycleweld C-3 cement produced bonds sufficiently strong in lap-joint specimens of phenolic laminate so that the failure occurred in the material rather than in the adhesive; this was true in the tests made at 25° C and at −40° C.

With both adhesives the maximum shearing strength of Compreg lap-joint specimens was obtained when the strips to be adhered had been machined flat after a preheat treatment introduced for the removal of residual stresses.

The shear strengths of Cycleweld-bonded metal specimens were greater than those for the Ardux-bonded metal specimens at both 25° C and at -40° C. The strength of the former increased while the strength of the latter decreased when the test temperature was reduced from 25° C to -40° C.

The shear strength of the specimens of birch-faced plywood bonded to aluminum alloy with Cycleweld C-3 cement was much greater than the strength of the similar mahogany-faced plywood-aluminum-alloy specimens. With both plywoods the shear strengths of the lap-joint specimens were about the same for the uncoated and the resin-coated plywood; also the major portion of the failure generally occurred in the wood veneer rather than in the adhesive indicating that the strength of the wood was the governing factor. The shear strengths of the specimens made with the birch material were generally greater at -40° C than at 25° C; while the reverse was true for specimens containing the mahogany material.

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Washington, D. C., May 19, 1944.

Table 1. Materials Used in Tests of Bonding Strengths of Adhesives.

Material Designation	Description of Material	Average Thickness in.
AD-17	24ST Alclad aluminum alloy.	0.017
AD-25	24ST Alclad aluminum alloy.	0.025
AD-26	24ST Alclad aluminum alloy.	0.026
AD-31	24ST Alclad aluminum alloy.	0.033
D-10	Aluminum alloy 24S-RT (coefficient of linear thermal expansion 23 x $10^{-6}/^{\circ}C$).	0.0123
D-22	24ST Aluminum alloy.	0.021
D-25	24ST Aluminum alloy.	0.026
D-30	24ST Aluminum alloy.	0.030
SS	Stainless steel, (coefficient of linear thermal expansion 17.3 x $10^{-6}/^{\circ}C$).	0.0053
J-1	Magnesium alloy.	0.032
FL-1/16	Fabric-base phenolic laminate.	0.067
FL-1/16-A	Same type of material as FL-1/16 but different lot.	0.070
FL-1/4	Fabric-base phenolic laminate.	0.24
PL-1/16	Paper-base phenolic laminate.	0.066
PL-1/4	Paper-base phenolic laminate.	0.25
P7	Compreg; phenolic-resin-impregnated compressed maple veneers, 7-ply with grain in adjacent plies at 90°.	0.28
M	Three-ply plywood, 1/32-inch mahogany faces, 1/16-inch poplar core; phenolic resin glue.	0.125
MR	"M" plywood coated with a phenolic resin.	0.125
MRP	"M" plywood faced with 7-mil thick paper toweling impregnated with a phenolic resin.	0.128
B	Three-ply plywood, 1/32-inch birch faces, 1/16-inch poplar core; phenolic resin glue.	0.122
BR	"B" plywood coated with a phenolic resin.	0.121
BRP	"B" plywood facedwith 7-mil thick paper toweling impregnated with a phenolic resin.	0.126
B'	Three-ply plywood, 1/48-inch birch faces, 1/28-inch poplar core; phenolic resin glue.	0.070
B"	Five-ply birch plywood, 1/48-inch faces, 1/28-inch cross-bands, 1/32-inch core; phenolic resin glue.	0.135

Table 2.- Data for Lap-Joint Specimens Bonded with Cycle-Weld C-3 and Cured While Under Clamping Pressure.[a]

Material Designation	Temperature of Test	No. of Specimens	Length of Overlap, Average	Time to Break, Average	Shear Strength		Shear Strength per in. of bond width		Failure Data: Failed in Material		Failure Data: Failed in Adhesive, Average	Failure Data: Failed at Adhesive-Material Boundary, Average	Failure Data: Failed to Bond, Average
					Average	Range	Average	Range	Average	Range			
	°C.		in.	min.	lb/in²	lb/in²	lb/in	lb/in	%	%	%	%	%
AD-31	25	2	0.47	1.3	1740	1400-2070	800	710-890	0	0	71	20	9
	-37	2	0.50	2.1	2420	2110-2720	1220	1050-1390	0	0	11	74	15
D-10	25	3	0.50	4.2	1330	1270-1370	665	630-690	33	0-100	56	2	9
	-38	3	0.51	8.8	1500	1470-1530	760	735-780	33	0-100	33	33	1
D-25	25	2	0.51	1.7	2000	1940-2060	1020	990-1050	0	0	56	44	0
S8	25	3	0.51	4.5	2530	2360-2670	1280	1200-1360	0	0	89	9	2
	-45	3	0.46	4.7	3040	2750-3490	1385	1350-1410	0	0	20	78	2
FL-1/16	25	3	0.51	3.5	780	720-830	400	345-430	32	0-96	32	34	2
	-42	2	0.50	1.6	730	700-750	360	350-375	98	98	0	0	2
PL-1/16	25	3	0.49	1.2	650	650-660	320	315-325	94	93-95	0	0	6
	-42	3	0.49	1.2	500	460-570	245	220-280	100	100	0	0	0

a. Curing conditions: 30 to 40 minutes in an oven at 155° to 165°C.

Table 3.- Data for Lap-Joint Specimens Bonded with Ardux 1 and Cured While Under Clamping Pressure.[c]

Material Designation	Temperature of Test	No. of Specimens	Length of Overlap, Average	Time to Break, Average	Shear Strength		Shear Strength per in. of Bond Width		Failure Data				
									Failed in Material		Failed in Adhesive, Average	Failed at Adhesive-Material Boundary Average	Failed to Bond, Average
					Average	Range	Average	Range	Average	Range			
	°C		in.	min.	lb/in²	lb/in²	lb/in	lb/in	%	%	%	%	%
AD-17	25	1	0.48	1.0	960	960	460	460	0	0	27	58	15
	-45	3	0.51	1.1	625	560-730	320	290-375	0	0	12	80	8
AD-31	25	2	0.52	1.0	1170	1140-1190	600	590-610	0	0	59	29	12
	-42	2	0.52	0.9	820	820	425	425	0	0	64	30	6
D-10	25	2	0.51	0.5	610[a]	600-610	310[a]	300-310	0	0	20	75	5
	-45	3	0.51	1.2	720	620-800	370	315-410	0	0	37	53	10
D-25	25	2	0.50	0.4	230[b]	130-320	110[b]	60-160	0	0	0	95	5
SS	25	3	0.51	1.5	1060	900-1190	550	470-610	0	0	4	91	5
	-44	3	0.51	2.1	870	790-910	440	400-460	0	0	15	81	4
FL-1/16	25	3	0.51	2.5	940	910-970	480	450-500	100	100	0	0	0
	-44	3	0.49	3.4	1130	920-1280	550	430-640	100	100	0	0	0
FL-1/4	25	3	0.47	2.7	2240	2220-2250	1050	1030-1080	98	94-100	2	0	0
	-44	3	0.50	2.8	2420	2380-2490	1200	1190-1220	93	90-97	7	0	0
PL-1/16	25	3	0.50	1.3	660	630-700	335	320-350	99	97-100	0	0	1
	-45	3	0.50	1.4	640	610-710	325	320-330	100	100	0	0	0
PL-1/4	25	3	0.48	1.6	2080	1930-2220	1000	980-1020	99	99-100	0	0	1
	-42	3	0.49	2.0	1990	1900-2040	980	970-990	99	96-100	0	0	1

[a] One specimen broke in handling; probably gluing was defective.

[b] Did not bond on first attempt to make specimens.

[c] Curing conditions: 25 to 30 minutes in an oven at 145° to 155°C.

Table 4. Shear Strength of Lap-Joint Specimens as a Function of Length of Overlap for Fabric-Base Phenolic Laminate FL-1/16-A Bonded with Ardux 1.

Overlap		No. of Specimens	Shear Strength		Shear Strength per inch of Bond Width	
Nominal in.	Average of Measured Values in.		Average lb/in²	Range lb/in²	Average lb/in	Range lb/in
1/8	0.13	3	2330	2200-2500	305	300-310
1/2	0.51	3	810	800-830	415	410-420
1-1/2	1.52	3	370	360-390	570	550-590

Table 5.- Mean Tensile Stress at Maximum Load in Lap-Joint Specimens.

Material Designation	Temperature[a] of Test	Mean Tensile Stress[b]	
		Cycle-Weld-Bonded Specimens (Table 2)	Ardux-Bonded Specimens (Table 3)
	°C	lb/in²	lb/in²
AD-17	25	--	--
	-40	--	--
AD-31	25	24,000	18,000
	-40	34,000	13,000
D-10	25	54,000	25,000
	-40	62,000	30,000
D-25	25	39,000	4,200
SS	25	240,000	100,000
	-40	260,000	80,000
FL-1/16	25	6,000	7,200
	-40	5,400	8,200
FL-1/4	25	--	4,200
	-40	--	4,800
PL-1/16	25	4,800	5,100
	-40	3,700	4,900
PL-1/4	25	--	4,000
	-40	--	3,900

[a]Low temperature value is approximate; exact values are in Tables 2 and 3.

[b]Calculated as the ratio of the maximum load to the cross-sectional area of a single strip of the material bonded.

Table 6. Effect of Heat on Tensile Strength of Sheet Materials Used in this Investigation.

Material Designation	Type of Material	Unheated Specimens: No. of Specimens	Unheated Specimens: Tensile Strength Average lb/in^2	Unheated Specimens: Tensile Strength Range lb/in^2	Heated Specimens: No. of Specimens	Heated Specimens: Tensile Strength Average lb/in^2	Heated Specimens: Tensile Strength Range lb/in^2
AD-17	Aluminum alloy	3	53,000	49,000-57,000	3[a]	58,000	57,000-60,000
D-10	do.	3	62,000	57,000-65,000	3[a]	61,000	56,000-66,000
SS	Stainless steel	3	245,000	240,000-250,000	3[a]	240,000	230,000-240,000
FL-1/16	Fabric-base phenolic laminate	2	13,500	13,000-14,000	2[b]	12,250	12,000-12,500
FL-1/4	do.	3	14,700	14,500-15,200	3[a]	14,200	14,100-14,300
PL-1/16	Paper-base phenolic laminate	3	21,800	16,000-26,000	3[b]	15,300	15,000-16,000
PL-1/14	do.	3	21,500	21,000-22,000	3[b]	18,700	18,000-19,000
P7	Compreg	3	15,800	13,000-17,000	3[a]	12,900	12,700-13,300

[a]These specimens were heated in an oven at 150°C for 40 minutes.

[b]These specimens were heated in an oven at 150°C for 40 minutes while clamped to steel plates.

Table 7.- Shear Test Data for Lap-Joint Specimens of Compreg and Phenolic Laminates Bonded with Cycle-Weld C-3 Under Spring Pressure.[c]

Material Designation[a]	Temperature of Test	No. of Specimens	Length of Overlap, Average	Time to Break, Average	Shear Strength		Shear Strength per in. of Bond Width		Failure Data				
									Failed in Material		Failed in Adhesive, Average	Failed at Adhesive-Material Boundary, Average	Failed to Bond, Average
					Average	Range	Average	Range	Average	Range			
	°C		in.	min.	lb/in²	lb/in²	lb/in	lb/in	%	%	%	%	%
P7-us	25	2	0.52	-	40	35-45	20	17-23	0	0	0	90	10
P7-ua	25	2	0.52	3.0	1350	1270-1420	705	670-740	52	6-97	8	38	2
P7-hs	25	2	0.50	1.7	810	810	405	370-440	0	0	0	63	37
P7-ha	25	2[b]	0.50	2.0	1240	1090-1390	600	540-680	0	0	5	69	26
P7-hms	25	2	0.55	3.3	2360	2180-2530	1295	1200-1390	46	38-54	51	3	0
	-51	2	0.52	5.0	2510	2310-2700	1295	1180-1410	99	99	0	1	0
P7-hma	25	2	0.55	2.9	2490	2370-2600	1370	1260-1480	52	5-99	45	1	2
	-47	2	0.52	4.3	2730	2720-2730	1430	1420-1440	98	97-99	0	0	2
PL-1/4-us	25	3	0.50	3.4	2100	2030-2150	1060	1010-1100	34	4-54	43	20	3
	-47	3	0.50	4.6	2850	2700-3040	1420	1380-1490	69	29-89	0	31	0
PL-1/4-ua	25	3	0.49	2.0	1910	1750-2010	930	870-980	37	27-48	45	0	18
	-45	3	0.49	2.3	2960	2240-3320	1450	1140-1620	91	85-96	1	0	8
PL-1/4-hs	25	3	0.49	2.4	1480	1360-1720	720	650-860	11	0-26	35	7	47
	-46	3	0.51	1.9	2660	2410-2820	1355	1250-1430	61	7-92	3	22	14
PL-1/4-ha	25	3	0.50	1.7	1840	1670-2070	910	840-990	52	22-73	23	1	24
	-45	3	0.50	1.7	2520	2120-3270	1265	1090-1600	95	94-96	0	0	5

[a]Types of treatment are indicated by letters after the material designation as follows:

u = unheated
h = heated
m = machined
s = unabraded
a = abraded

[b]Two other specimens came apart on handling.

[c]Curing conditions: 150 to 200 lb/in² pressure in an oven at about 163°C until the temperature at the bond had been 163°C for 25 minutes.

Table 8.- Shear Test Data for Lap-Joint Specimens of Compreg and Phenolic Laminates Bonded with Ardux 1 Under Spring Pressure.[c]

Material Designation[a]	Temperature of Test	No. of Specimens	Length of Overlap, Average	Time to Break, Average	Shear Strength		Shear Strength per in. of Bond Width		Failure Data				
									Failed in Material		Failed in Adhesive,	Failed at Adhesive-Material Boundary,	Failed to Bond,
					Average	Range	Average	Range	Average	Range	Average	Average	Average
	°C		in.	min.	lb/in²	lb/in²	lb/in	lb/in	%	%	%	%	%
P7-us	25	6	0.52	Two specimens came apart in handling; four broke while being placed in grips.									
P7-ua	25	3	0.59	2.1	1440	980-2010	850	600-1250	-	-	-	-	-
	-42	2[b]	0.53	2.8	1460	1290-1630	760	710-810	1	0-3	9	82	8
P7-hs	25	2	0.52	Specimens came apart while being placed in grips.									
P7-hms	25	2	0.49	2.2	2180	2170-2180	1060	1000-1130	100	100	0	0	0
	-51	2	0.52	4.4	2180	1960-2410	1130	1080-1180	100	100	0	0	0
P7-hma	25	2	0.56	2.1	2020	1730-2320	1130	980-1280	100	100	0	0	0
	-50	2	0.56	3.9	2080	1950-2220	1180	1050-1310	58	15-100	3	39	0
FL-1/4-us	25	2	0.51	3.2	2040	2000-2080	1040	1040	97	96-98	0	0	3

[a]Types of treatment are indicated by letters after the material designation as follows:

u = unheated
h = heated
m = machined
s = unabraded
a = abraded

[b]One specimen came apart while being placed in grips.

[c]Curing conditions: 150 to 200 lb/in² pressure in an oven at about 145°C for 60 minutes.

Table 9.- Shear Test Data for Lap-Joint Specimens Made by Bonding Together Mahogany-Faced Plywood and Aluminum Alloy with Cycle-Weld C-3.[d]

Specimen Designation[d]	Form of Adhesive[a]	Pressure Method[b]	Temperature of Test	No. of Specimens	Length of Overlap, Average	Time to Break, Average	Shear Strength		Shear Strength per in. of Bond Width		Failure Data			
											Failed in Wood		Failed at Adhesive-Material Boundary, Average	Failed to Bond,[c] Average
							Average	Range	Average	Range	Average	Range		
			°C		in.	min.	lb/in^2	lb/in^2	lb/in	lb/in	%	%	%	%
AD-26/M	L	C	25	3	0.51	1.9	800	680-930	405	340-480	96	89-100	0	4
			-40	1	0.50	1.5	420	----	205	----	89	----	0	11
AD-26/MR	L	C	25	2	0.51	2.2	830	750-900	415	390-440	99	99-100	0	1
			-42	2	0.50	2.2	590	570-610	295	285-305	99	99-100	0	1
AD-26/MRP	L	C	25	2	0.52	1.0	410	390-420	210	200-220	100	100	0	0
			-40	2	0.52	2.0	550	530-570	280	270-290	100	100	0	0
AD-26/M	F	C	25	2	0.48	1.3	680	670-690	330	330	76	72-80	24	--
			-47	2	0.50	1.6	590	470-700	290	230-350	90	88-92	10	--
D-22/M	L	C	25	3	0.51	1.9	760	660-860	390	340-430	96	86-100	0	4
D-22/MR	L	C	25	3	0.51	1.9	780	780-790	400	390-410	99	98-100	0	1
D-22/MRP	L	C	25	3	0.50	1.7	490	470-510	250	240-260	99	99-100	0	1
D-22/M	F	C	25	3	0.52	1.4	640	490-780	340	260-430	77	70-81	23	--
D-30/M	F	P	25	3	0.49	1.5	650	610-690	320	300-340	96	90-99	4	--
			-41	3	0.49	1.6	490	480-520	240	230-250	99	99-100	1	--
D-30/MR	F	P	25	3	0.52	1.6	620	560-720	320	280-400	98	96-100	2	--
			-45	3	0.52	2.4	560	460-620	290	250-320	100	100	0	--

[a]L = liquid brushed on; F = film.

[b]C = spring-clamp apparatus; P = electrically heated press.

[c]Refers to fusion of the Cycle-Weld coatings on two halves of a specimen; does not apply to specimens bonded with film.

[d]The symbols to the left and right of the diagonal, respectively, indicate the sheet materials which were bonded together. The sheet materials are identified in table 1.

[e]Curing conditions:

Spring-clamp apparatus: 100 to 300 lb/in^2 pressure in an oven at about 163°C for 50 to 60 minutes; temperature at the bond was 163°C for at least 25 minutes.

Electrically heated press: Approximately 200 lb/in^2 pressure at 165°C; temperature at the bond was 163°C for at least 15 minutes.

Table 10.- Shear Test Data for Lap-Joint Specimens Made by Bonding Together Birch-Faced Plywood and Aluminum Alloy with Cycle-Weld C-3.[f]

Specimen Designation[e]	Form of Adhesive[a]	Pressure Method[b]	Temperature of Test	No. of Specimens	Length of Overlap, Average	Time to Break, Average	Shear Strength Average	Shear Strength Range	Shear Strength per in. of Bond Width Average	Shear Strength per in. of Bond Width Range	Failure Data: Failed in Wood Average	Failure Data: Failed in Wood Range	Failure Data: Failed at Adhesive-Material Boundary, Average	Failure Data: Failed to Bond,[d] Average
			°C		in.	min.	lb/in²	lb/in²	lb/in	lb/in	%	%	%	%
AD-25/B	L	C	25	3	0.51	1.6	1220	1100-1430	625	550-730	17	8-30	73	10
			-42	3	0.50	4.0	2100	1810-2280	1045	940-1100	100	99-100	0	0
AD-25/BR	L	C	25	3	0.52	2.2	1370	1250-1490	715	640-780	88	82-92	5	7
			-40	3	0.51	4.9	1710	1590-1870	870	830-960	100	100	0	0
AD-25/BRP	L	C	25	3	0.51	1.6	1100	1070-1130	560	530-600	98	98	0	2
			-40	3	0.52	3.6	1270	1180-1400	660	610-710	100	100	0	0
D-30/B	L	C	25	3	0.52	1.7	1270	1000-1560	660	530-810	57	36-70	40	3
			-40	3	0.52	3.0	1290	1080-1490	670	550-790	24	1-70	76	0
D-30/B[c]	L	C	25	3	0.51	1.0	500	400-590	255	215-295	96	95-98	3	1
			-42	3	0.52	1.5	490	460-510	255	245-265	100	100	0	0
D-30/BR	L	C	25	3	0.53	1.6	1260	1140-1390	670	600-725	66	22-93	29	5
			-42	3	0.52	4.0	1590	1400-1730	830	730-900	96	94-97	3	1
D-30/BRP	L	C	25	3	0.52	2.2	1170	1150-1210	610	590-630	97	96-98	1	3
			-42	3	0.51	2.7	1110	850-1410	560	435-720	100	100	0	0
D-30/B	F	C	25	3	0.49	0.9	670	610-790	330	285-410	18	3-43	82	--
			-45	3	0.50	2.3	850	780-900	425	385-450	62	0-95	38	--
D-30/B[c]	F	C	25	3	0.52	0.9	490	430-540	255	225-290	83	55-98	17	--
			-48	3	0.51	1.4	430	340-480	220	180-240	2	0-6	98	--
D-30/B'	F	P	25	3	0.52	1.7	1290	1260-1320	670	650-690	8	5-12	92	--
			-42	3	0.50	2.4	1390	520-1930	700	260-970	90	70-100	10	--
D-30/B"	F	P	25	4	0.51	1.6	1320	720-1580	670	390-790	68	5-96	32	
			-42	3	0.51	2.6	1200	910-1490	600	480-700	72	16-100	28	--

[a]L = liquid brushed on; F = film.
[b]C = spring-clamp apparatus; P = electrically-heated press.
[c]Face grain perpendicular to length of specimen.
[d]Refers to fusion of the Cycle-Weld coatings on the two halves of a specimen; does not apply to specimens bonded with film.
[e]The symbols to the left and right of the diagonal, respectively, indicate the sheet materials which were bonded together. The sheet materials are identified in table 1.
[f]Curing conditions:

Spring-clamp apparatus: 100 to 300 lb/in² pressure in an oven at about 163°C for 50 to 60 minutes; temperature at the bond was 163°C for at least 25 minutes.

Electrically heated press: Approximately 200 lb/in² pressure at 165°C; temperature at the bond was 163°C for at least 15 minutes.

Table 11.- Shear Test Data for 24ST Alclad Aluminum Alloy-Magnesium Alloy Specimens (AD-25/J) Bonded with Cycle-Weld C-3.[a]

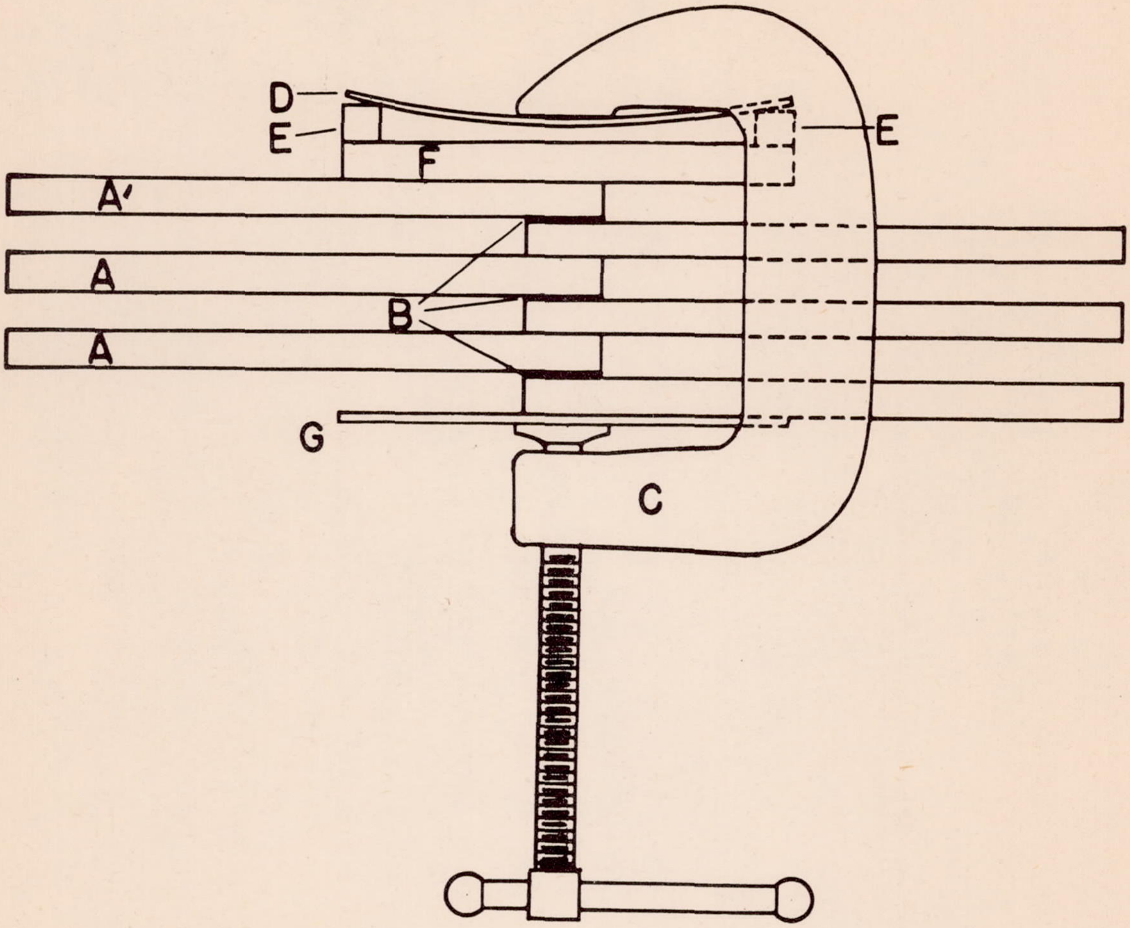
Method of Bonding Specimens	Temperature of Test	No. of Specimens	Length of Overlap, Average	Time to Break, Average	Shear Strength		Shear Strength per in. of Bond Width		Failure Data			
					Average	Range	Average	Range	Failed in Material	Failed in Adhesive	Failed at Adhesive-Material Boundary[b]	Failed to Bond
	°C		in.	min.	lb/in^2	lb/in^2	lb/in	lb/in	%	%	%	%
Spring-Clamp Apparatus	25	3	0.51	1.3	1510	1130-1720	770	590-870	0	ca.10	55	ca.35
	-43	3	0.51	3.8	2540	2260-2700	1290	1170-1380	0	0	68	32
Steam Press	25	3	0.51	1.0	700	400-1110	350	210-560	0	0	96	4
	-47	3	0.51	2.2	1860	1620-2220	940	810-1130	0	0	95	5

[a]Curing conditions:

Spring-clamp apparatus: 300 to 500 lb/in^2 pressure for 75 minutes in an oven at 165°C.

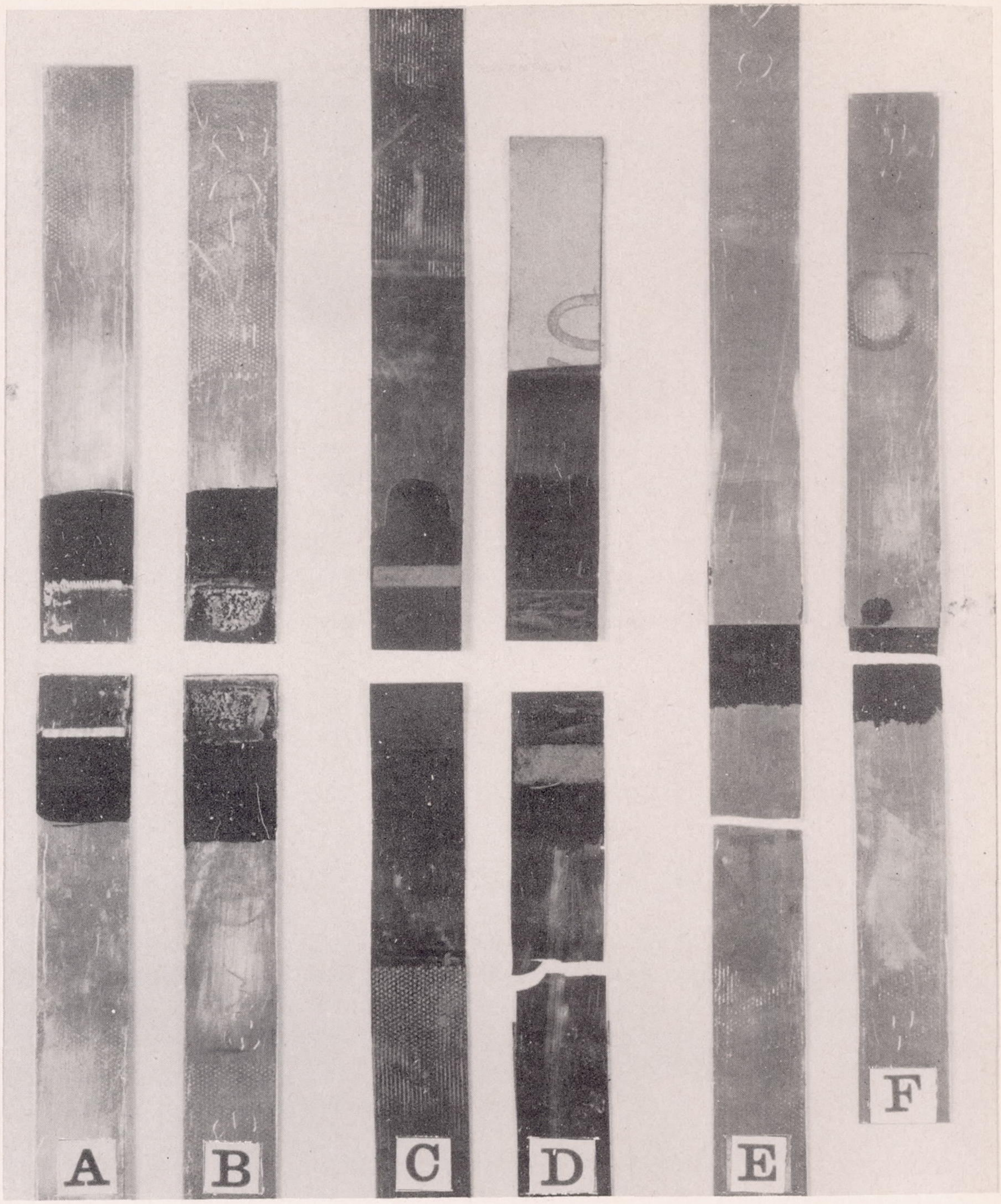
Steam press: Approximately 500 lb/ in^2 pressure for 20 to 25 minutes at 165°C.

[b]Failure was generally at the magnesium alloy-adhesive boundary.



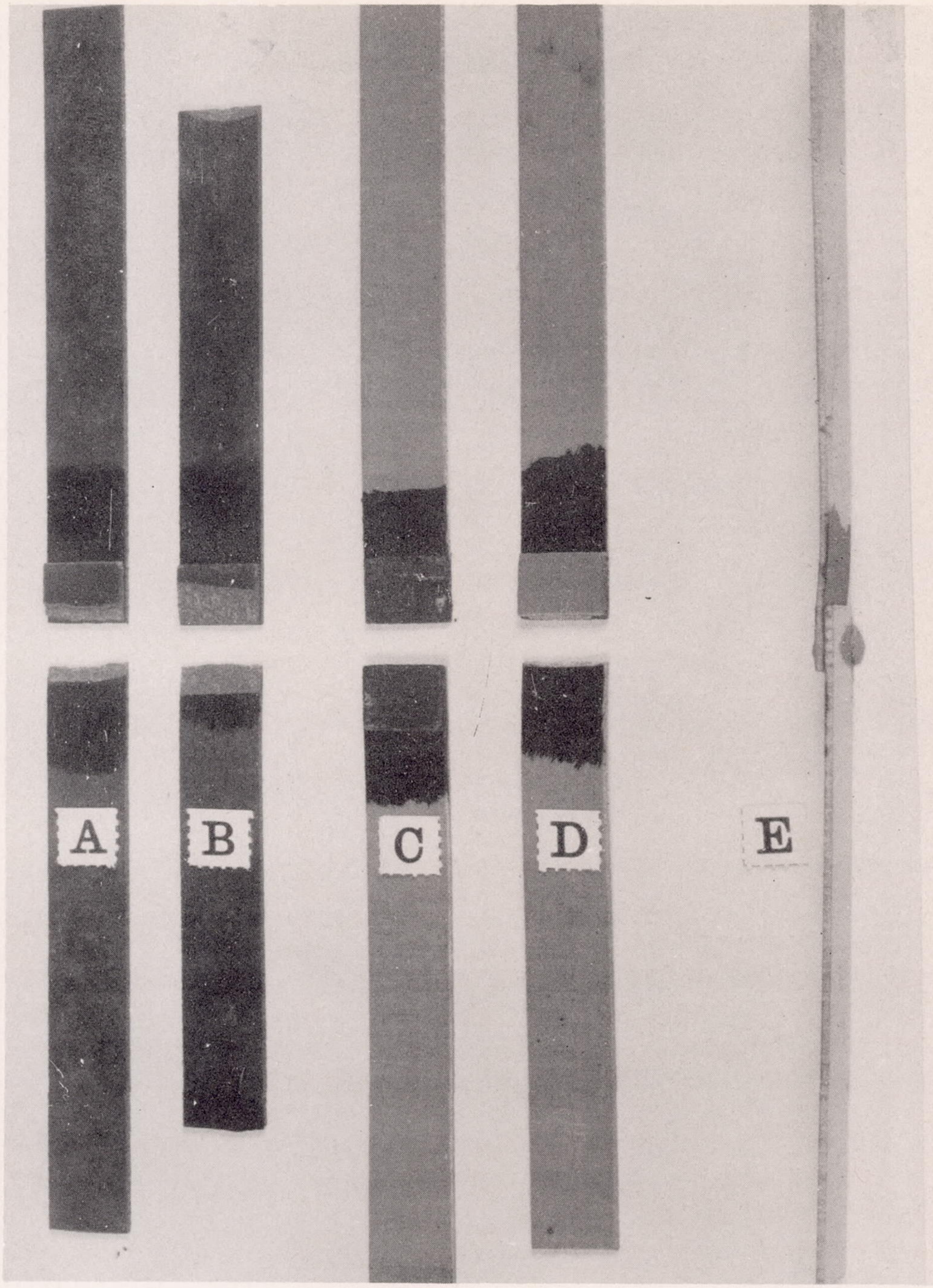
A, Specimen; B, Cement; C, C-clamp; D, Spring-steel strip 0.04-inch thick, 3/4-inch wide, 3-inches long; E, support blocks glued to F; F, 3 by 3/4 by 1/4-inch steel bar; G, flat metal strip 1/16-inch thick by 3/4-inch wide.

Figure 1.- Spring-clamp apparatus for making lap-joint specimens.



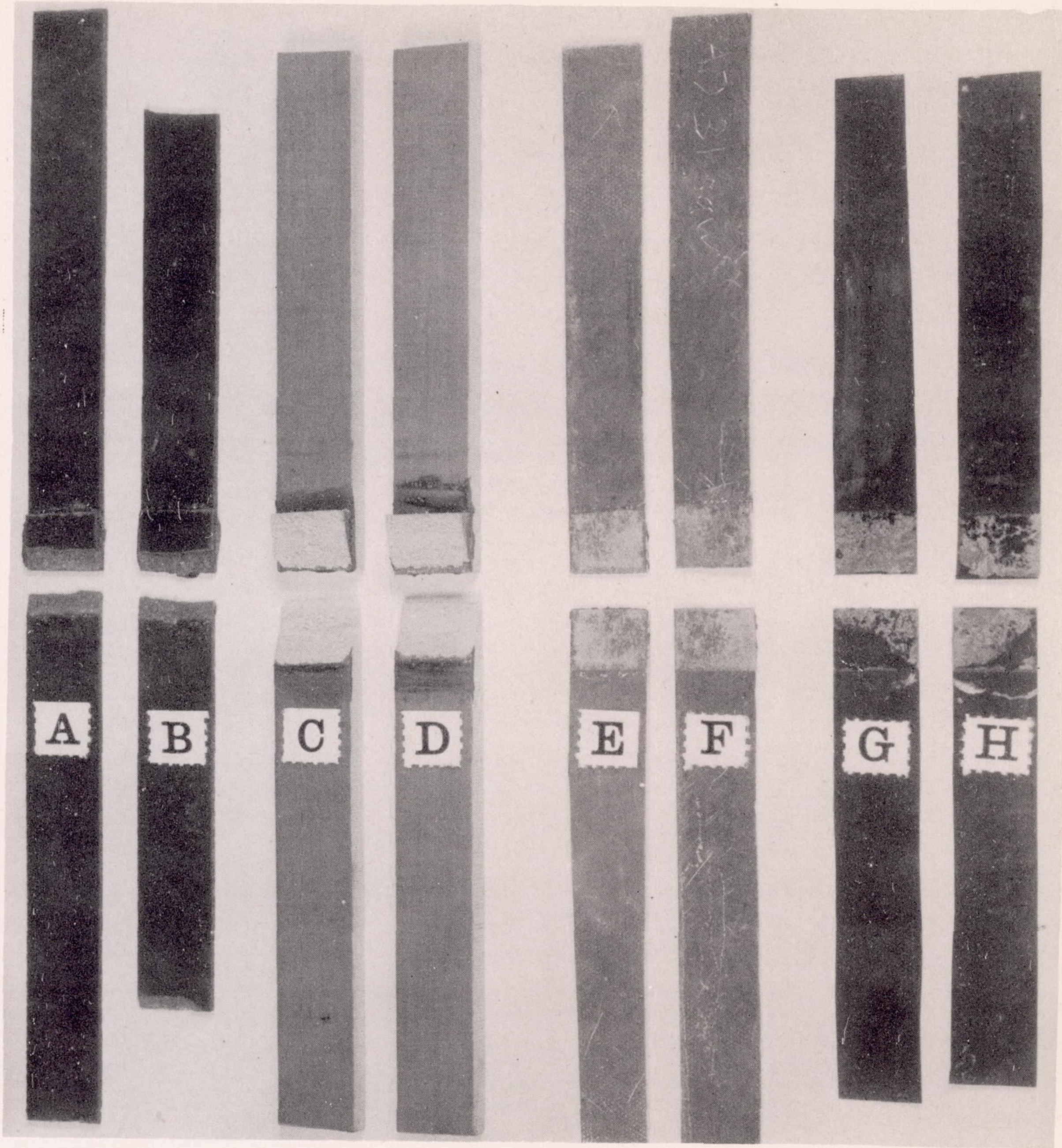
A, Alclad aluminum alloy (AD-31) tested at 25° C.
B, Alclad aluminum alloy (AD-31) tested at -40° C.
C, Stainless steel (SS) tested at 25° C.
D, Stainless steel (SS) tested at -40° C.
E, Aluminum alloy (D-10) tested at 25° C.
F, Aluminum alloy (D-10) tested at -40° C.

Figure 2.- Cycle-Weld-bonded metal lap-joint specimens after test.



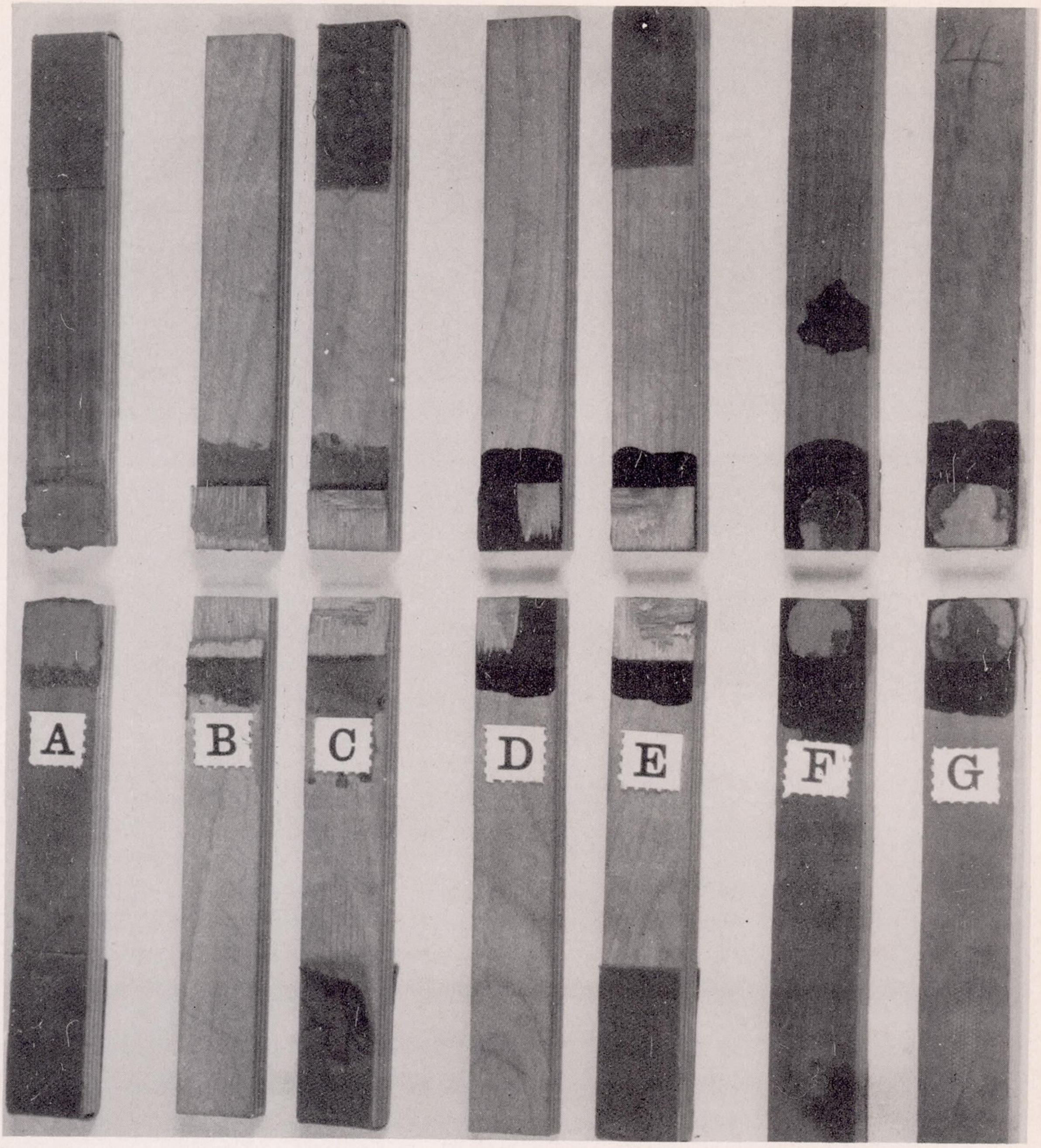
A, Paper-base phenolic laminate (PL-1/16) tested at 25° C.
B, Paper-base phenolic laminate (PL-1/16) tested at -40° C.
C, Fabric-base phenolic laminate (FL-1/16) tested at 25° C.
D, Fabric-base phenolic laminate (FL-1/16) tested at -40° C.
E, Bending of phenolic laminate (FL-1/16) specimen during cure.

Figure 3.- Cycle-Weld-bonded phenolic laminate specimens after test.



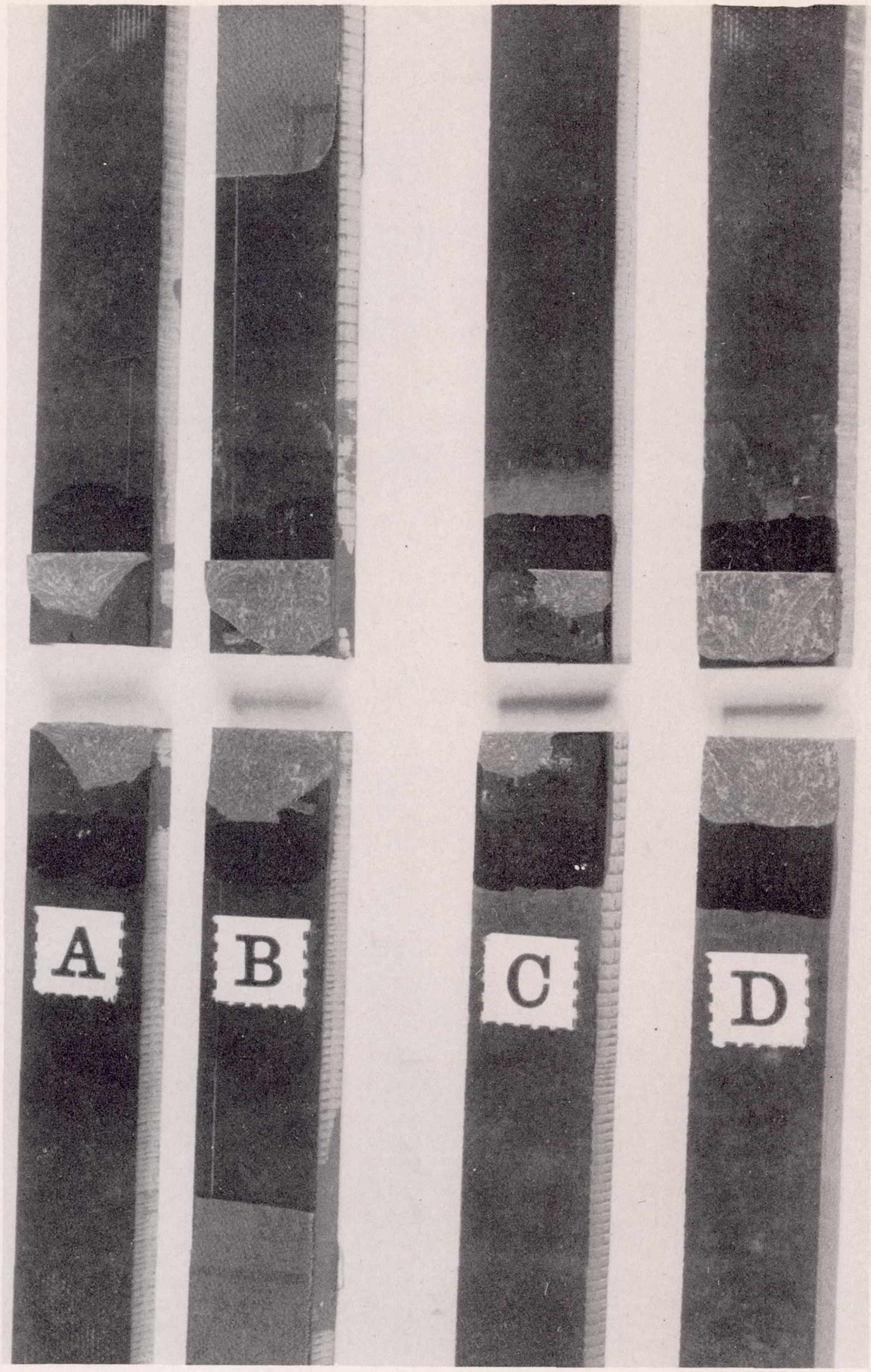
A, Paper-base phenolic laminate (PL-1/16) tested at 25° C.
B, Paper-base phenolic laminate (PL-1/16) tested at -40° C.
C, Fabric-base phenolic laminate (FL-1/4) tested at 25° C.
D, Fabric-base phenolic laminate (FL-1/4) tested at -40° C.
E, Alclad aluminum alloy (AD-31) tested at 25° C.
F, Alclad aluminum alloy (AD-31) tested at -40° C.
G, Stainless steel (SS) tested at 25° C.
H, Stainless steel (SS) tested at -40° C.

Figure 4.- Ardux-bonded lap-joint specimens.



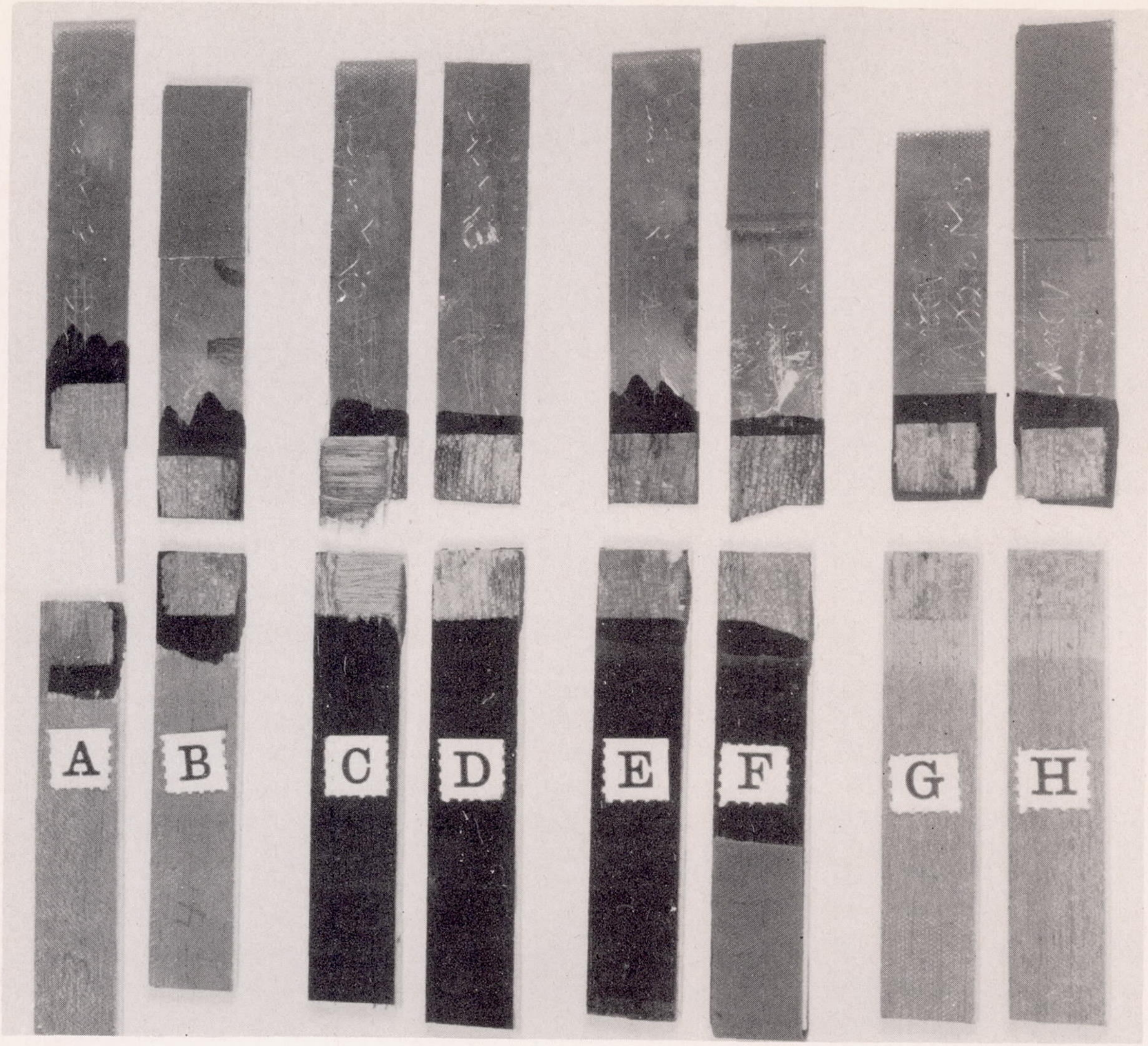
A, Bonded with Ardux 1; not preheated, surface abraded; tested at -40° C.
B, Bonded with Ardux 1; preheated, machined and abraded; tested at 25° C.
C, Bonded with Ardux 1; preheated, machined and abraded; tested at -40° C.
D, Bonded with Cycle-Weld C-3; preheated, machined; tested at 25° C.
E, Bonded with Cycle-Weld C-3; preheated, machined; tested at -40° C.
F, Bonded with Cycle-Weld C-3; preheated; tested at 25° C.
G, Bonded with Cycle-Weld C-3; preheated, abraded; tested at 25° C.

Figure 5.- Compreg lap-joint specimens.



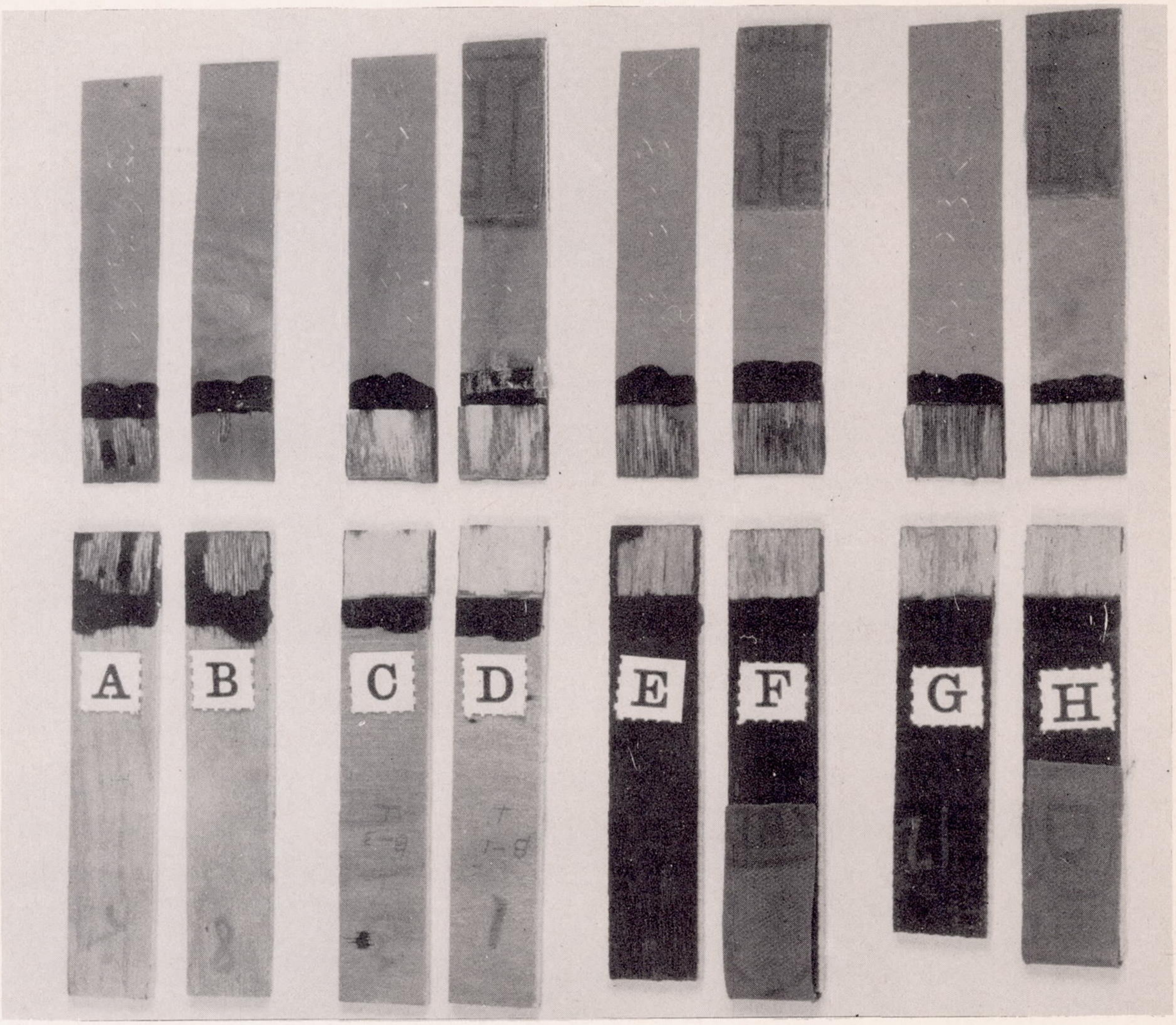
A, Not preheated; tested at 25° C.
B, Not preheated; tested at -40° C.
C, Not preheated, abraded; tested at 25° C.
D, Not preheated, abraded; tested at -40° C.

Figure 6.- Paper-base phenolic laminate (PL-1/4) bonded in "spring-clamp" apparatus with Cycle-Weld adhesive.



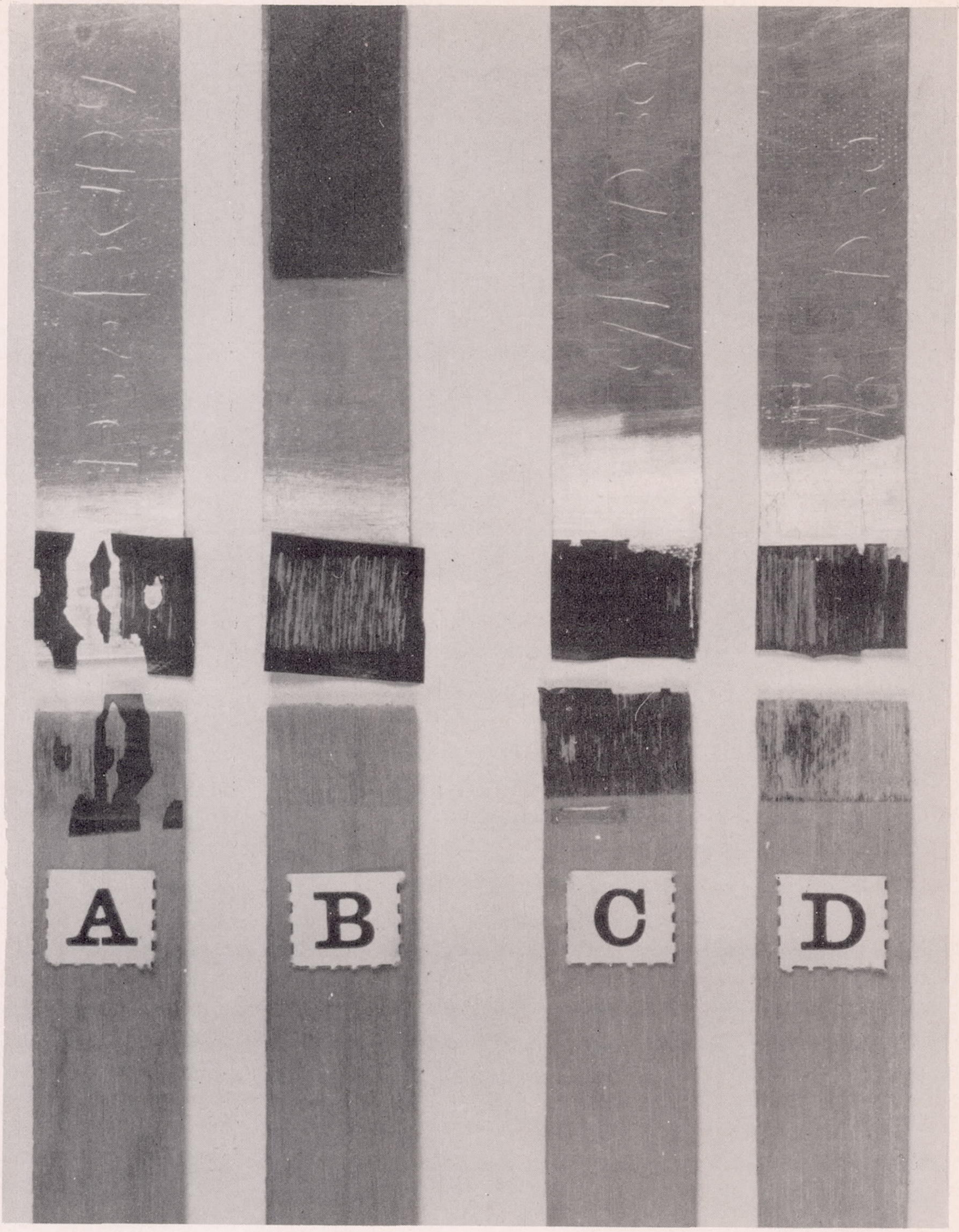
A, Surface untreated (AD-26/M); tested at 25° C.
B, Surface untreated (AD-26/M); tested at -40° C.
C, Surface resin-coated (AD-26/MR); tested at 25° C.
D, Surface resin-coated (AD-26/MR); tested at -40° C.
E, Surface resin-paper-coated (AD-26/MRP); tested at 25° C.
F, Surface resin-paper-coated (AD-26/MRP); tested at -40° C.
G, Surface untreated (AD-26/M); Cycle-Weld film; tested at 25° C.
H, Surface untreated (AD-26/M); Cycle-Weld film; tested at -40° C.

Figure 7.- Alclad aluminum alloy bonded with Cycle-Weld C-3 to mahogany plywoods having various surface treatments.



A, Surface untreated (D-30/B); tested at 25° C.
B, Surface untreated (D-30/B); tested at -40° C.
C, Same as A except face grain perpendicular to length of specimen; tested at 25° C.
D, Same as C, but tested at -40° C.
E, Surface resin-coated (D-30/BR); tested at 25° C.
F, Surface resin-coated (D-30/BR); tested at -40° C.
G, Surface resin-and-paper coated (D-30/BRP); tested at 25° C.
H, Surface resin-and-paper coated (D-30/BRP); tested at -40° C.

Figure 8.- Aluminum alloy bonded with Cycle-Weld C-3 to birch plywoods having various surface treatments.



A, D-30/B specimens, bonded with spring-clamp apparatus; tested at 25° C.
B, Same as A, but tested at -40° C.
C, D-30/B' specimens, bonded in electrically heated press; tested at 25° C.
D, Same as C, but tested at -40° C.

Figure 9.- Aluminum alloy bonded with Cycle-Weld film to untreated birch plywoods.